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F-REGION IRREGULARITIES STUDIED BY SCINTILLATION OF SIGNALS FROM SATELLITES

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ABSTRACT

Scintillation of radio signals from earth satellites has been studied for five years during the declining phase of the sunspot cycle. It is found that the character of the scintillation, and thus, probably, of the ionospheric irregularities that cause them, vary systematically with geomagnetic latitude, season of the year, time of day, and phase of the sunspot cycle. Nighttime scintillation occurs in the F-region, mainly at heights of about 350 km. This type of scintillation in most cases results from first-order scattering from weak, field-aligned irregularities in electron density, which may be caused by two-stream instabilities excited by "dumping" of electrons from the earth's radiation belts. Such scintillations are observed north of a certain parallel of geomagnetic latitude, the southern limit varying weakly with magnetic activity. Similar effects are observed in both Northern and Southern Hemispheres. Correlations of scintillation with other manifestations of ionospheric disturbances, including spread-F, red auroral arcs, magnetic activity and corpuscular counts, in the outer radiation belt, have been noted, and support the presumed association with leakage of electrons from the belt. Scintillation occurs much more frequently than any of these other phenomena, and may provide a more sensitive indication of the "dumping" process.

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I. INTRODUCTION

Ever since the vertical sounding observations of Booker and Wells in 1938 the irregular structure of the ionosphere has been a subject of continued interest. In 1946 renewed interest was generated when the intensity of the radiation from radio stars was observed to fluctuate (Hey, et al.,1946). Later, back-scatter sounding (Peterson, 1955), whistler-mode propagation (Helliwell, et al., 1956), satellite radio signals (Slee, 1958) and rocket sounding (Calvert, et al., 1962) all indicated the existence of irregularities. Despite the number of papers that have been written on the subject, knowledge of the subject is mostly phenomenological and the causative mechanisms remain unknown. Only recently has a theory successfully explained certain equatorial sporadic E irregularities connected with the electrojet current (Farley, 1963, Maeda, et al., 1963) and perhaps also E region irregularities in the auroral zone. The theory seems to be confirmed experimentally (Bowles, et al., 1963). However, irregularities in the F region in temperate latitudes are also observed regularly and a theory to explain them has yet to be developed.

In this paper are summarized observations of satellite radio signal scintillation during the descending half of the solar cycle. Some pertinent information and sample records illustrating different effects are presented in Part I. Statistical properties of the amplitude of the received wave are given in Part II. Since the satellite covers a wide geographic region during each pass the geometry is constantly changing. In Part III factors relating to the geometry of the problem are discussed. The average behavior of irregularities is summarized in Part IV. In Part V are discussed possible connections of irregularities with other phenomena such as red auroral arcs and the

Table 1. Some Pertinent Information on Satellites Used in this Study

Name	Launching Date	Radio Cutoff Date	Frequencies Transmitted mc/s	Apogee km	Perigee km	Inclination degrees
1958 δ 2 (Sputnik 3)	May 15, 1958	April 6, 1960	20	no longer in orbit		65.4
1959 ι 1 (Explorer 7)	October 13, 1959	Still in orbit	20	1076	551	50.31
1961 O 1 (Transit 4A)	June 29, 1961	Still transmitting	54	985	893	66.81
1961 α-γ 1 (Discoverer 32, Nora-Alice 1)	October 13, 1961	November 13, 1961	20	no longer in orbit		81.62
1961 α-κ 1 (Discoverer 36, Nora-Alice 2)	December 12, 1961	March 8, 1962	20 and 40	no longer in orbit		81.20

"dumping" of electrons from the outer radiation belt. It appears from preliminary data that the dumping is strong enough to excite two-stream instabilities. Semi-quantitative arguments are used to investigate this possibility in Part VI. This theory, if accepted, can explain some of the experimental observations.

I-1 Satellites and Transmitting Frequencies

The satellites utilized in this study are listed in Table 1.

I-2 Locations of Observer

Data have been obtained from the following locations:

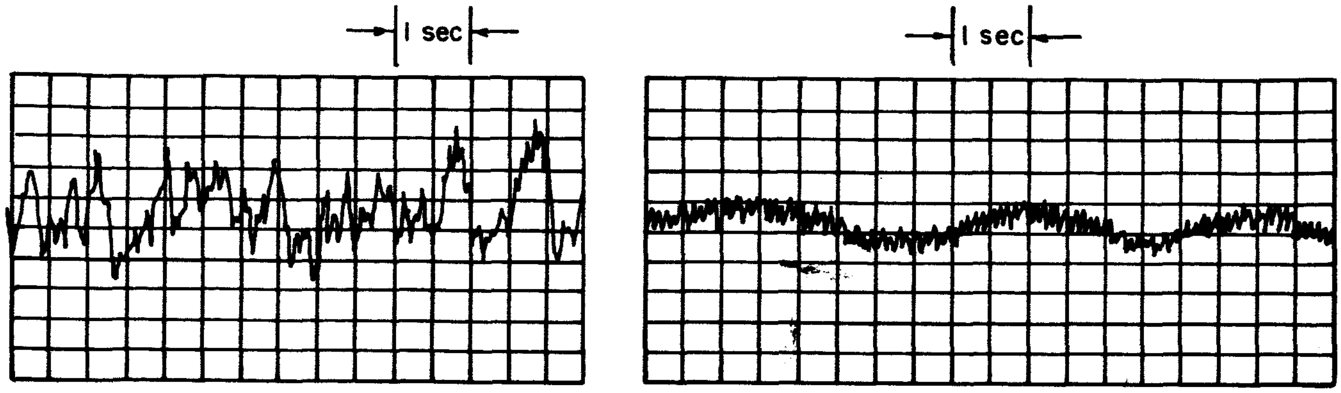
Table 2. Geographic Coordinates of Observing Stations

Station	Latitude	Longitude	Data Communicated by
Urbana	40.018°N	88.327°W	University of Illinois
Baker Lake	64.3°N	96.1°W	University of Illinois
Aberystwyth	52.4°N	4.1°W	University College of Wales (W.J.G. Beynon)
Blaxland	33.75°S	209.4°W	Radio Research Board Laboratory (G.H. Munro)
Lower Hutt	41.2°S	185.1°W	Dominion Physical Laboratory (J. Mawdsley)
Stanford	37.4°N	122.6°W	Stanford University (O.K. Garriott)

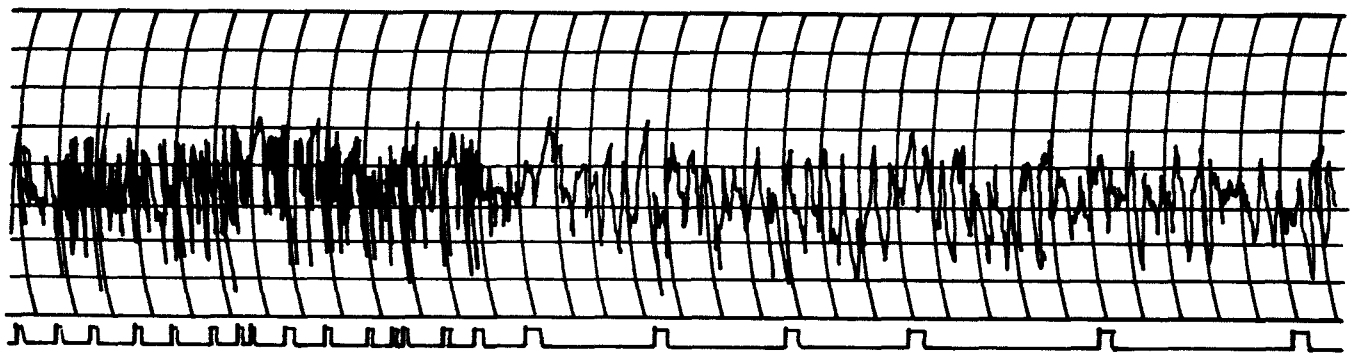
The receiving and recording techniques utilized in this study have been discussed elsewhere (Swenson, 1962).

I-3. Sample Records

Fig. 1 displays some typical samples of amplitude scintillation records. It is obvious that the scintillation rate at Urbana is much lower than at



(a) URBANA, 2343 CST, JAN 23, 1960. (LEFT TRACE SHOWED SCINTILLATION, RIGHT TRACE NO SCINTILLATION, NOTE THE SPIN AND FARADAY FADINGS.)



(b) BAKER LAKE, 1015 CST. JAN. 10, 1960. (SECOND MARKS ON THE LOWER SCALE.)

Fig. 1 Sample Scintillation Records on 20 mc/s (1959 Iota 1)

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Baker Lake.

As the sunspot number and the average scintillation activity declined, lens-like diffraction was observed at times. Fig. 2 shows one such record. This is probably the same phenomenon observed by Wild and Roberts (1956). In this investigation the scintillation phenomenon shown in Fig. 1 is studied, rather than the phenomenon shown in Fig. 2

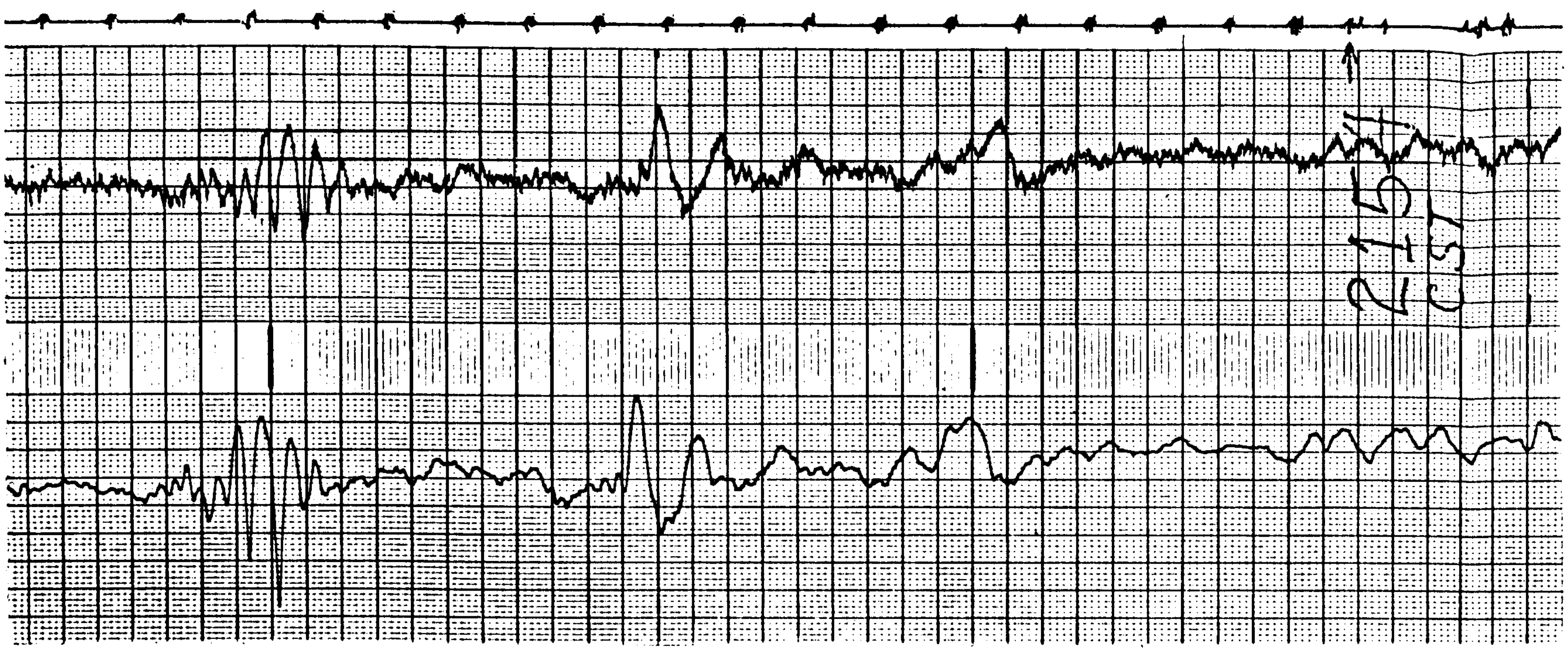

Fig. 2 Sample Records Showing Diffraction from Lens-Like Irregularities (54 mc/s, 1961 Omicron, April 4, 1962). The upper trace was for a receiver spaced 2.9 km from the receiver of the lower trace. Time goes from left to right with second marks indicated at the top.

II. STATISTICS OF DATA

Here we give the statistics of the data from which the present investigation is based.

II-1. Statistics of Data

In the study of seasonal behavior the following definitions are adopted:

Spring: Feb. 15 - May 15

Summer: May 15 - Aug. 15

Fall: Aug. 15 - Nov. 15

Winter: Nov. 15 - Feb. 15 (next year).

In Table 3 the numbers of Urbana records used in the study are listed. Only passages corresponding to satellite height 300 km or above are used. This accounts for the small number of passages in the fall season of 1959 when sattelite 1958 δ was in a low orbit and 1958 ι not yet launched.

Table 3. Number of Passes Recorded at Urbana

20 mc/s(1958 Delta 2 and 1959 Iota)

Fall 58	Winter 58	Spring 59	Summer 59	Fall 59	Winter 59	Spring 60
42	61	41	67	7	53	48

Summer 60	Fall 60
32	21

54 mc/s (1960 Iota)

Spring 62	Summer 62	Fall 62	Winter 62
82	66	81	76

Since the signal from 1958 Delta 2 was keyed and that from 1959 Iota showed pronounced spin fading a completely quantitative definition of scintillation index is not possible. In order to show the semiquantitative behavior scintillation indices 0, 1 and 2 are assigned to portions of amplitude records by visual inspection. The procedure was used in a previous paper (Yeh and Swenson, 1959) and has been adopted by other observers (Liszka, 1963a). In investigating the average behavior of scintillation it is also convenient to present the scintillation index on a percentage basis. Here we use a linear scale so that the average scintillation index of 2 corresponds to 100%, 1 to 50%, etc. Since 1960 Iota 1 is transmitting on 54 mc/s with no undesirable modulation, a more quantitative definition of scintillation index is possible. If A_o is the average value of the amplitude (or the amplitude in the absence of irregularities) and ΔA the fluctuations the scintillation is defined as

$$S = \left\langle \left(\frac{\Delta A}{A_o} \right)^2 \right\rangle^{1/2}$$

We note that S^2 is essentially the ratio of the "noise" power to the average power.

According to these definitions of scintillation index Table 4 gives the percent occurrences of each kind of scintillation record of interest. This table shows that the scintillation near sunspot minimum (1961 Omicron data) is not appreciably less common than that near sunspot maximum (1958 .

Delta and 1959 Iota) even though it is shown in Part VI that the activity is much weaker as the sunspot number decreases. Note that transitions occurred 21% of the time near sunspot maximum and only 7% of the time near sunspot minimum.

Table 4. Scintillation Statistics

1958 δ 2 and 1959 ι (20 mc/s)	
No scintillation in the entire pass	33%
S = 2 for the entire pass	7%
At least part of the pass has S = 0	87%
At least part of the pass has S = 2	33%
At least part of the pass has scintillation	67%
Transition observed from S = 0 to 2 or vice versa	21%
1961 O (54 mc/s)	
No scintillation in the entire pass	37%
$0 < S \leq 0.2$ for the entire pass	38%
$0.2 < S$ for the entire pass	25%
At least part of the pass has S = 0	70%
At least part of the pass has $0 < S \leq 0.2$	50%
At least part of the pass has $S > 0.2$	25%
Transition observed from S = 0 to $S > 0.2$ or vice versa	7%

II-2 Amplitude Probability Density

In the presence of irregularities the wave is scattered; hence, the signal when received on the ground is the resultant of a large number of vectors. When the scattering is sufficiently intense so that the amplitude of these vectors is random and the phase is uniformly distributed the distribution of the amplitude is Rayleigh, otherwise it is some generalization of Rayleigh distribution. If in addition to these random vectors there is a constant vector the amplitude becomes Rice-distributed (Rice, 1944-45). The Rice distribution approaches the Gaussian distribution as the constant vector becomes relatively large. Most of the scintillation records show Gaussian distribution. But at Baker Lake in 1959 and 1960 the amplitude may also have Rice and even Rayleigh distributions, indicating the existence of multiple scattering. Fig. 3 shows a few amplitude distributions.

II-3 Autocorrelation Function

Fig. 1 showed that the scintillation rate at Baker Lake is much faster than that at Urbana. A similar effect is also shown in Fig. 4 where typical correlation functions of these two stations are plotted. These autocorrelation functions are very similar to those obtained theoretically (Yeh, 1962).

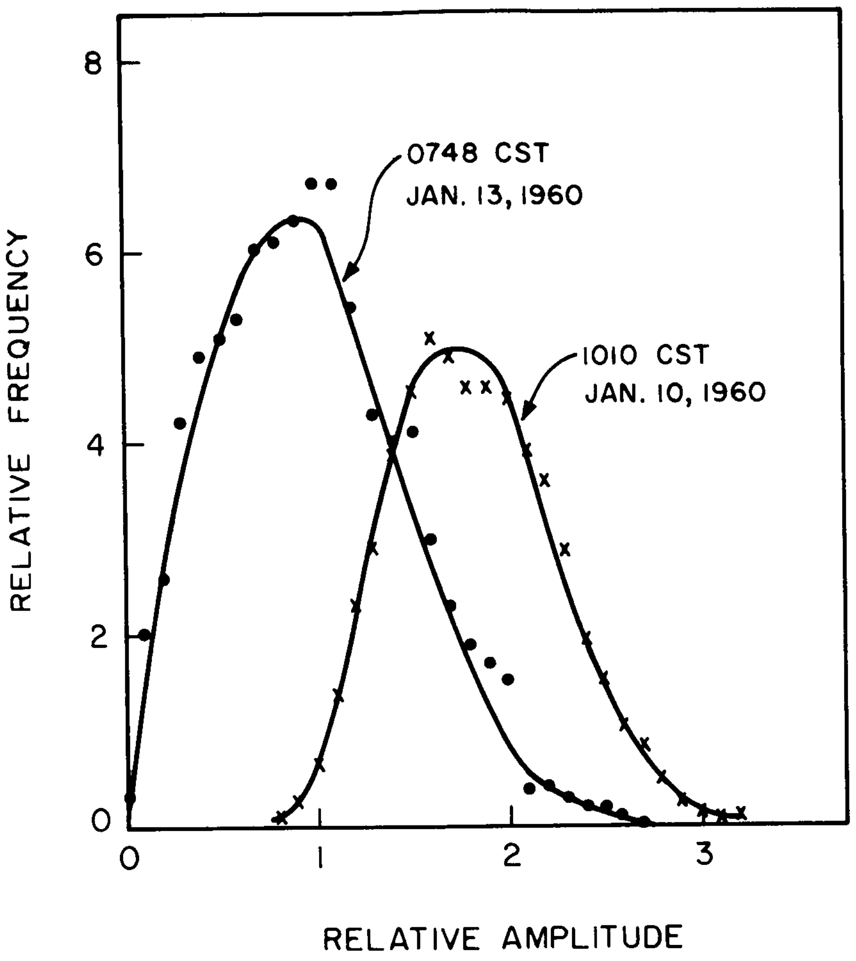

Fig. 3 Examples of Amplitude Distributions
(20 mc/s. Baker Lake)

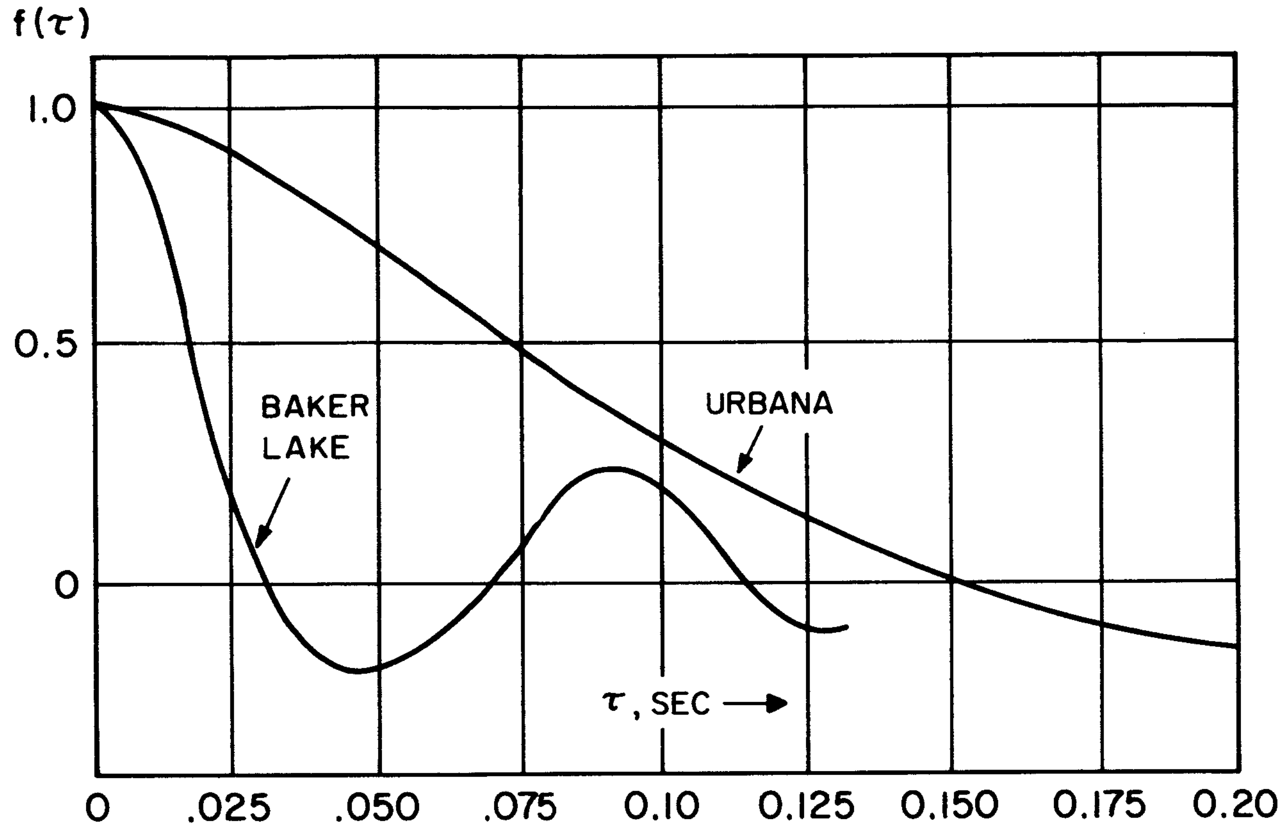

Fig. 4 Auto-Correlograms of Scintillating Amplitude of Satellite Signals on 20 mc/s.

III. DEPENDENCE OF SCINTILLATION ON GEOMETRY

The study of scintillation is complicated by its dependence on geometry. Before proceeding to study the properties of scintillation-producing irregularities it is important to understand the geometrical aspects of the problem. In his important review paper, Booker (1958) examined the zenith angle dependence of the amplitude scintillation and found disagreement between his simple theory and the experimental results obtained at Manchester and thus termed anomalous the Manchester zenith angle data. Further observations (Little, et al., 1962) confirmed earlier Manchester results concerning the relative absence of zenith angle effect--much below Booker's theoretically predicted values. In the meantime further theoretical calculations (Yeh, 1962; Briggs and Parkin, 1963) also demonstrated that the weak dependence of scintillation on zenith angle for a high latitude station is attributable to the compensating effects of magnetic field alignment of anisotropic irregularities and the effective thickness of the region of irregularities.

There is at present enough experimental evidence to indicate beyond question that the scintillation-producing irregularities are in the ionosphere, ranging from 100 km up to perhaps 1000 km (For discussion on heights, see Chivers, 1963). Indications are that the region may be quite thin at times and may also be thick at other times, depending on the degree of disturbance and the geomagnetic location of the observer. It is also found experimentally that irregularities may be at different heights in different parts of the sky (Yeh, et al., 1963). These irregularities are really fluctuations in the electron density, hence the stochastic nature of the problem. The correlation function of the density fluctuations has ellipsoidal symmetry with dimensions of the order 1 km by 5-10 km and with major axis aligned with the Earth's magnetic field lines (Spencer, 1955; DeBarber, et al., 1962). The anisotropic nature of these irregularities introduces added complications in the theory but they are very essential in order to interpret correctly the experimental data. Therefore, the physical model usually chosen is either a plane slab or a spherical shell whithin which are contained anisotropic fluctuations in the dielectric constant (or the electron density). The receiver is situated approximately 300 km below the slab (or shell) and the transmitter may be anywhere from the bottom of the slab (or shell) to an infinite distance above the slab. In order to simplify the theory further the slab is vaguely termed "thin" to suit one's convenience. This practice gives no region of validity of the theory, especially as the slab may also be quite thick (hundreds of kilometers) in which case the thin slab theory no longer applies.

III-1. Zenith Angle Dependence

If the electron density fluctuation is assumed to be a stationary process (with respect to spatial coordinates), the amplitude and the phase of the wave after passing through the slab region are not necessarily stationary in the statistical sense (with respect to time) as the satellite speeds across the sky. The non-stationarity comes about because of three factors: the change in the effective thickness of the slab, the change in the direction of propagation with respect to the elongation of the correlation function of the electron density, and the change in the effective distances between the transmitting satellite and the slab and between the slab and the receiver. The effect of the last factor is relatively small in a single satellite passage and we shall temporarily ignore it and take it up again in a later section.

A theoretical discussion of the zenith angle dependence is given by Briggs and Parkin (1963) using the "phase changing screen" concept and the diffraction theory. Using the scattering approach, a study of two special cases has been carried out (Yeh, 1962) and it is shown that for a station with magnetic dip angle 70° the zenith angle dependence is expected to be weak.

Experimental study of the zenith angle dependence is difficult because of the scintillation dependence on other factors (e.g., geomagnetic latitude, etc.). Most of the radio star scintillation data (Booker, 1958; Little, et al., 1962) tend to support weak zenith angle dependence, especially if the angle is less than about 60°.

III-2. Size of Irregularities

In formulating the problem it is usually assumed that the correlation function of the dielectric constant or of the electron density is Gaussian with prolate spheroidal symmetry. The assumption of Gaussian shape is purely for convenience and has no physical basis. But even there the correlations of the amplitude and the phase are not necessarily Gaussian in general. It should also be cautioned that the correlation distances of the wave amplitude and phase are not simply obtained by introducing the geometric magnification factor even in the limit of weak scattering. Due to the anisotropic nature of these irregularities such a procedure may introduce a fifty percent error, which is appreciable in the more refined measurements.

It has been shown that the average maximum of the amplitude is uniquely related to the correlation distance for a given form of power spectrum (Rice, 1944 and 1945). Therefore, if the received signals (essentially narrow band noise) are assumed to have identical power spectra, the counting of maxima could give directly the size of irregularities. The assumption here is constancy in the shape of the power spectrum and it is very doubtful whether this is valid for scintillating signals. Nevertheless, from the standpoint of data analysis the counting of mazima is a much simpler and easier task than computation of correlation functions. For purposes of rough estimates the counting procedure will be used, keeping in mind that the values so obtained may be off by as much as fifty percent.

The results of such a rough analysis are shown in Table 5. Only portions of the records corresponding to satellite positions near points of closest approach to the receiving station have been used. Hence, the measured size is roughly the dimension perpendicular to the magnetic field lines since all listed stations have high magnetic dip angles. In Table 5 we see that the sizes measured at Houghton and Adak are nearly equal. Although Adak is at a higher latitude than Houghton, they are really very close to the same auroral isochasm, as derived theoretically by Vestine and Sibley (1960). This observation suggests a connection between the scintillation and the geomagnetic field. It is also interesting to note that the sizes are larger at Houghton than at either higher (Baker Lake) or lower (Urbana) magnetic latitudes. It is not yet known whether this is a genuine effect that holds at all times or whether it was true only during the three months that observations were made.

Before leaving this section it should be mentioned that the size obtained depends on a theory which assumes "weak" scattering. This assumption appears to be valid in most cases on 20 mc/s (See III-5). However, in January, 1960 the scintillation at Baker Lake was extremely violent and the amplitude may even have a Rayleigh probability density (See Fig. 3), suggesting that multiple scattering must be taken into account. Therefore, the value of 0.26 km given for Baker Lake station in Table 5 must be taken as a lower limit.

Table 5. Scintillation Rate (peaks/sec) and "Size (km)" of Irregularities Perpendicular to the Earth's Magnetic Field Lines

		Baker Lake	Houghton	Adak	Urbana
January 1960	Rate	30 ± 6	-	-	-
(1958 Δ_2, 20 mc/sec)	"Size"	0.26 ± 0.07*	-	-	-
December 1961 - February 1962	Rate	8.0 ± 4.9	1.5 ± 0.7	1.3 ± 0.5	2.6 ± 0.7
(Nora-Alice II, 20 mc/sec)	"Size"	1.8 ± 1.4	5.4 ± 2.0	5.8 ± 2.0	3.0 ± 0.7

*This value may be in error due to possible presence of multiple scattering.

III-3. Height of Irregularities

The earliest study of irregularity heights was made by means of the vertical incidence sounder (Booker and Wells, 1938). Only when the irregularities appear below the peak of the F2 region can such measurements be made. In the case of radio star observations heights can be estimated approximately if there are simultaneous measurements of amplitude and phase scintillations (Hewish, 1952). Some of these early results have been summarized by Chivers

(1963). Since the advent of rockets and satellites, measurement techniques have been much improved. In a few cases, irregularities at heights from 400 km to 1000 km have been observed by means of rockets (Calvert, et al., 1962). Among the various satellite techniques, two give the most unambiguous results; both are spaced-receiver methods.

The first method makes use of the so-called "edge" effect. As mentioned in II-1, radio signals received from the satellite often display a sharp transition from slow, quasi-periodic, Faraday fading to fast, random fluctuations in amplitude, indicating that the ray has just intercepted and passed the edge of a patch containing irregularities. If two receivers are placed parallel to the subsatellite track and a distance somewhat more than 10 km apart, a difference of a few seconds is observed in the time of transition as seen from the two stations. By triangulation the height of the irregularities can be computed. This method has been used by a number of investigatiors (Parthasarathy et al., 1959; Munro, 1963). A sample record taken at the University of Illinois is shown in Figure 5. The height deduced for this record is 395 $\pm$ 10 km.

The second method depends on the correlation of the signals received by two closely spaced receivers. The spacing here is usually not more than a few kilometers. By noting the similar fades on two or more receivers the height can be computed by triangulation. This method has also been used by a number of investigators (Frihagen and Trøim, 1960; Basler and DeWitt, 1962; DeBarber, et al., 1962; Liszka, 1963 b Jespersen and Kamas, 1963). The results of all these investigations indicate that these irregularities may appear at heights ranging from 100 km to 1000 km above the surface of the Earth. Because of insufficient data these past results do not give statistical information

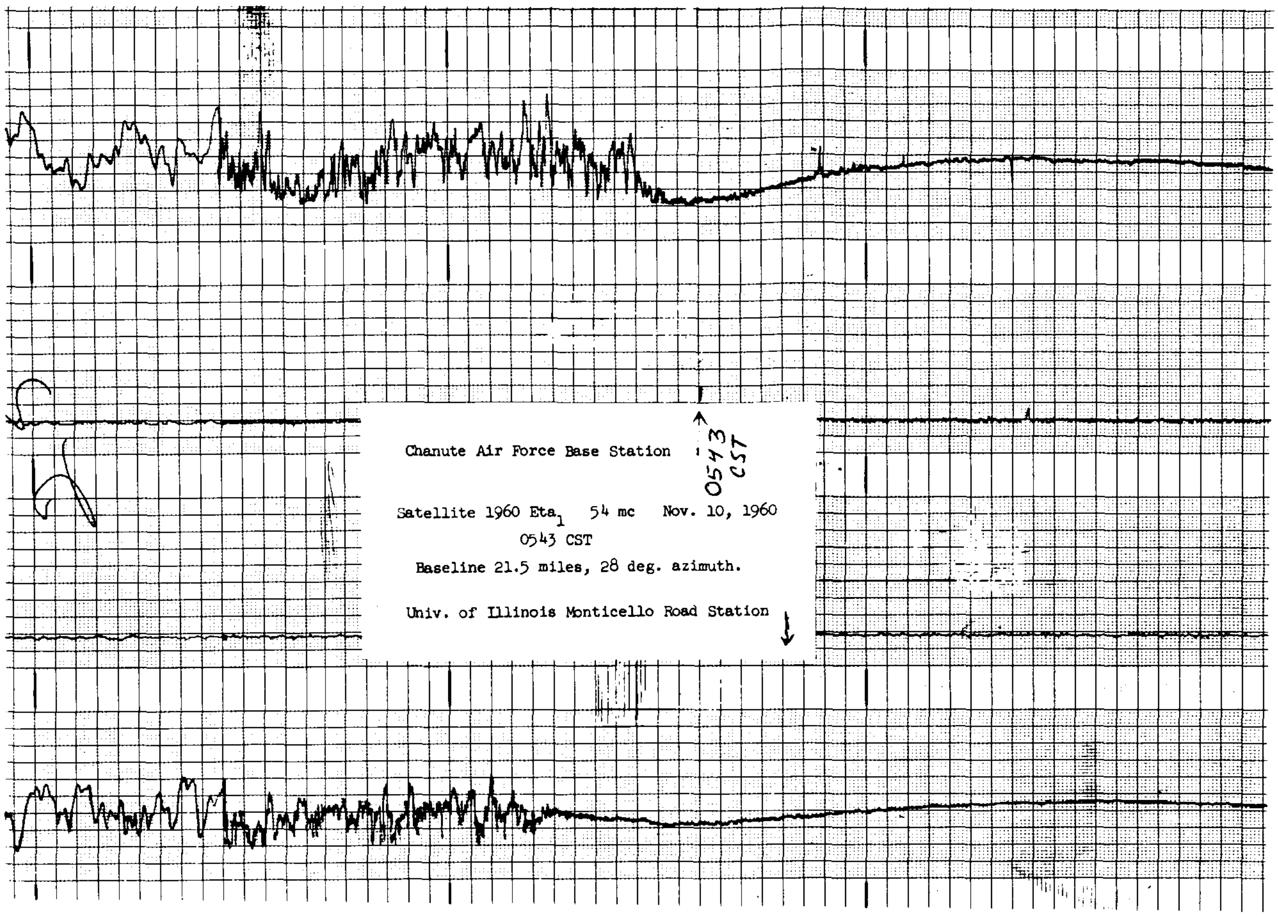

Fig. 5 Sample Records Showing Time Delay in the Onset of Scintillation (Edge Effect) (time delay = 5.25 $\pm$ 0.25 sec.)

about the height distribution of irregularities. The preliminary statistical study of such a nature at the University is summarized in Fig. 6. (This figure was first presented earlier [Yeh, et al., 1963] in slightly different form. The modification is necessary since a patch of irregularities of the same size will be observed a longer time if it is low than if it is high. We acknowledge here the work of J. P. McClure who is preparing a more extensive and detailed study of heights.) The data consist of approximately 150 minutes of scintillation records taken in 1962, mostly in November and December. Note that most of the irregularities are concentrated in the F-region in a narrow height range from 300 km to 400 km with a very minor secondary E-region peak. These data are very important in the search for an explanation of the existence of irregularities.

III-4. Height of Satellite

The problem of scintillation dependence on the height of the satellite has been studied theoretically (Yeh, 1962). It is shown that the amplitude scintillation increases monotonically, while the phase scintillation decreases monotonically, as the height of the satellite above the irregularities increases.

The corresponding experimental study is usually very difficult since the height of the satellite changes very slowly and during this time changes due to other effects (e.g., diurnal, seasonal, or the change in irregularity height etc.) may overshadow the relatively weak dependence on satellite height. On one occasion during the last few weeks of the life of Sputnik III (1958 Delta 2) it was possible to make a rough study of this nature. During these few weeks

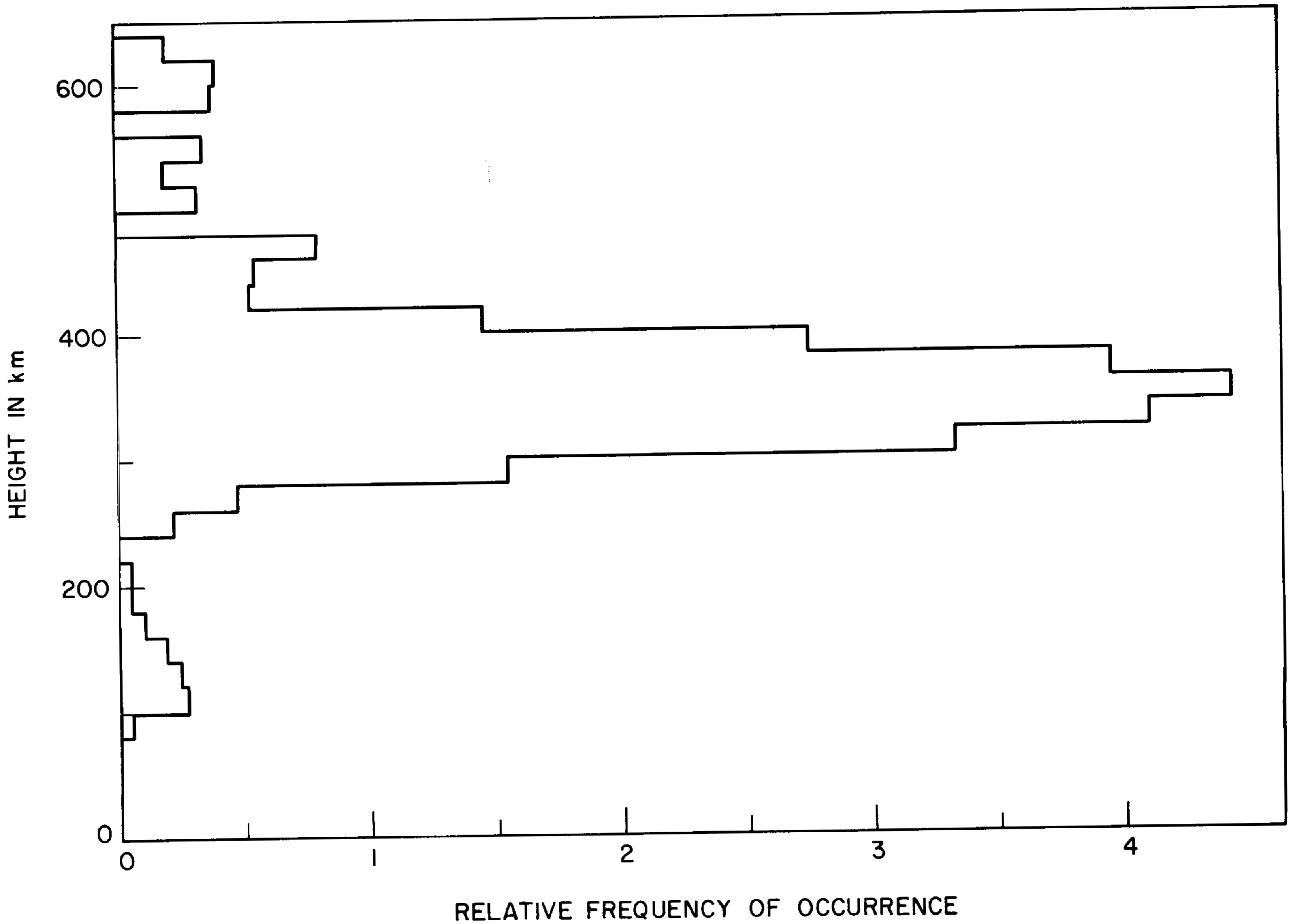

Fig. 6 Height Distribution of Irregularities

the orbital period was decreasing rapidly and the satellite was transmitting a c.w. signal on 20 mc/s, only when in sunlight. The scintillation index was obtained when the satellite was close to its point of closest approach at Baker Lake. The result is depicted in Fig. 7, which shows that as the satellite decreases in height the amplitude scintillation also decreases as predicted by the theory. There is also a large spread in these points, suggesting that even during the relatively short period of several weeks other effects are also important. Another feature of Fig. 7 is that the scintillation was negligible when the satellite was below about 200 km, which gives the lower boundary of the region of irregularities. This observation is in agreement with the height distribution given in Fig. 6.

III-5. Frequency Dependence

The dependence of scintillation on frequency is quite complicated because the geometry usually places the receiver at such a place that neither far-field nor near-field approximations are valid. The study of frequency dependence has been made with radio star scintillations (Chivers, 1960a). In the case of satellite scintillations such a study has been hampered by the lack of a suitable multi-frequency satellite and has yet to be undertaken. According to the weak-random-medium theory the average rate of scintillation is almost independent of frequency. This has been found to be true in scintillations of radio stars (Booker, 1958; Chivers, 1960). Some data collected at Urbana on 54 mc/s and 150 mc/s from 1961 Omicron are given in Fig. 8. The scintillation rate is defined here as the average number of peaks per second. The closeness of these points to the straight line indicates the lack of dependence on

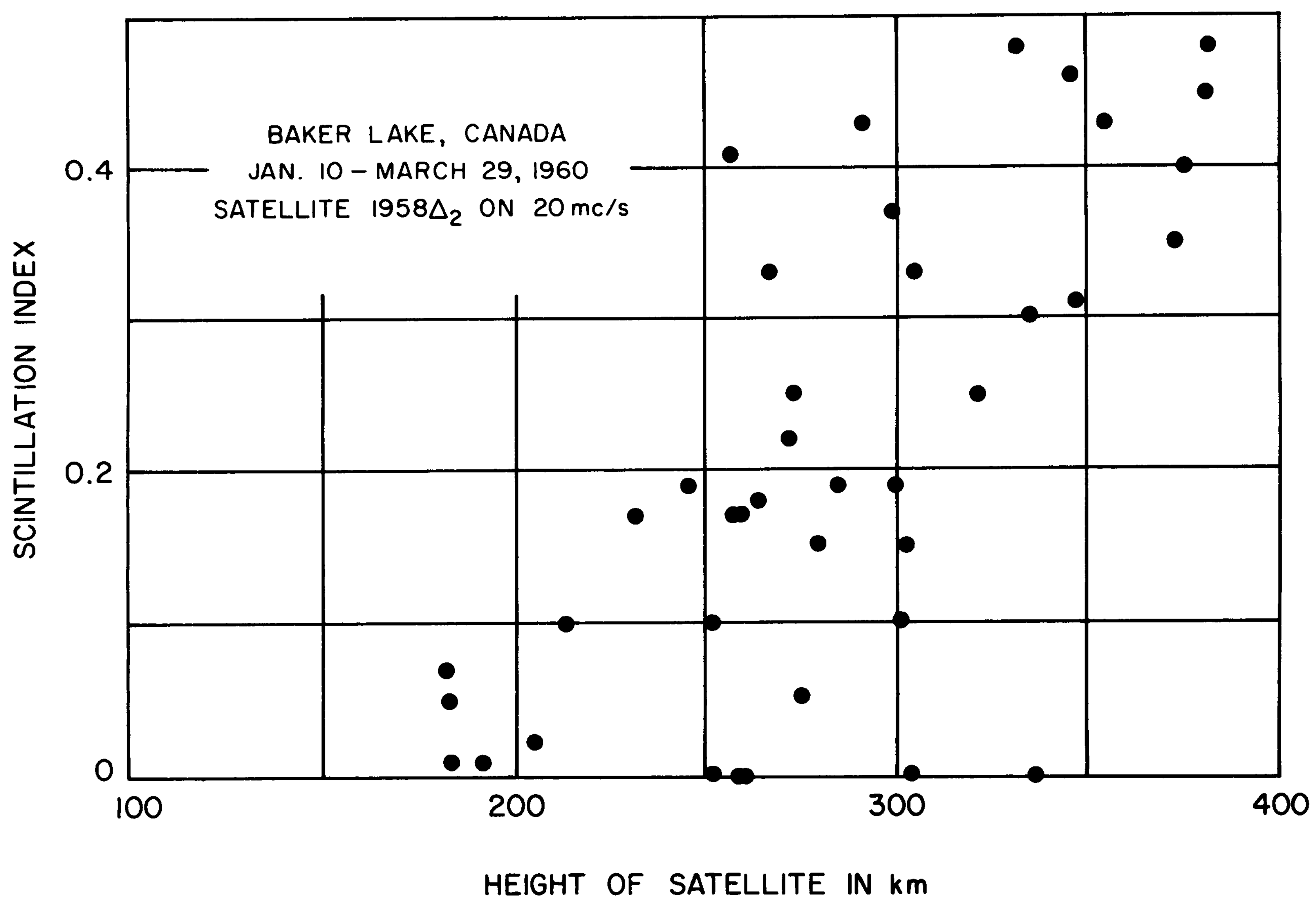

Fig. 7 Dependence of Scintillation on the Height of the Satellite

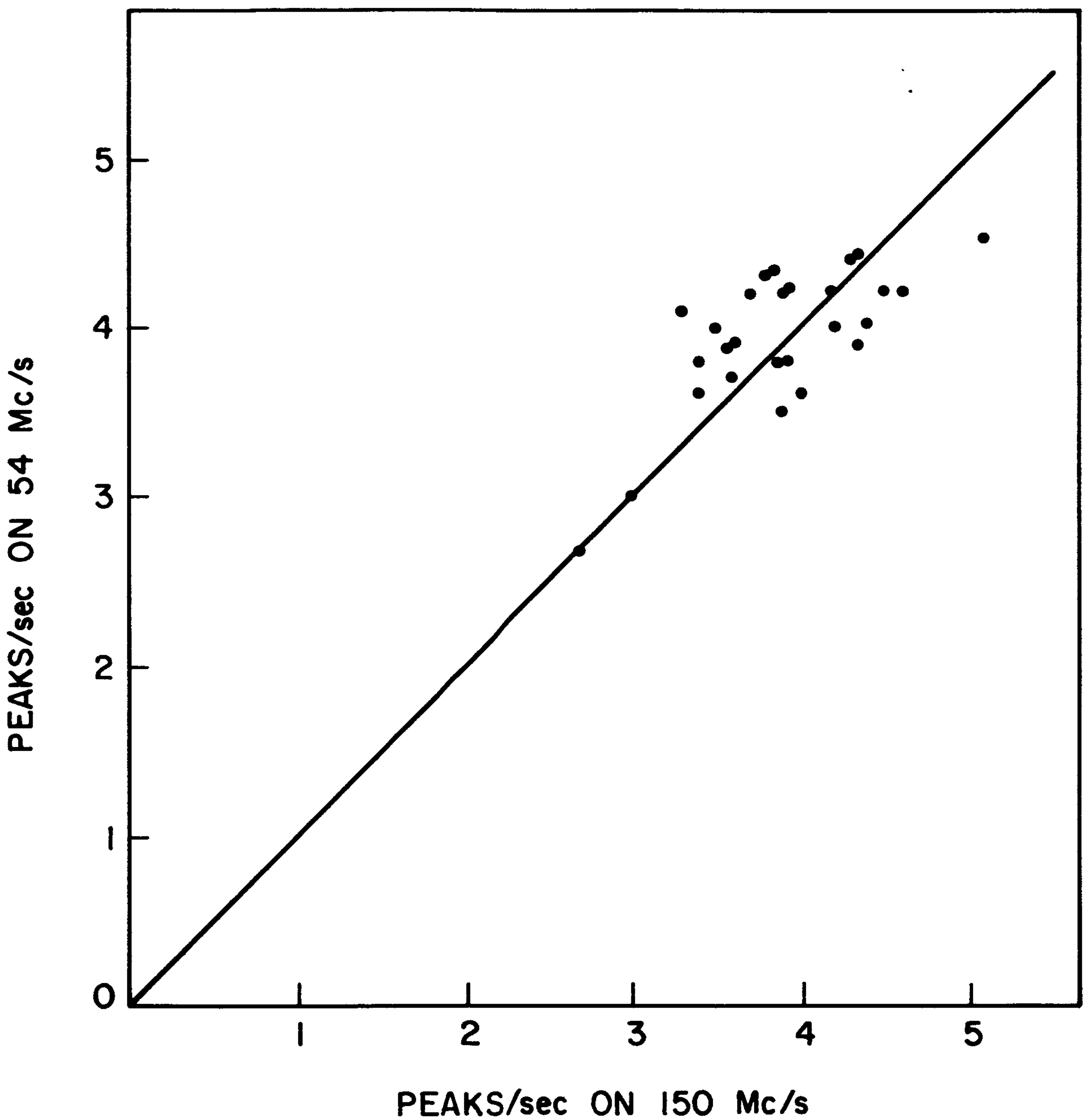

Fig. 8 Scintillation Rate Dependence on Frequency
March-Sept. 1962 (1961 Omicron)

frequency. This is an excellent check on the validity of application of the weak random medium theory. Hence, at least during the period investigated, the single-scatter theory of the weak random medium seems to be applicable at a frequency of 54 mc/s or higher.

IV. MORPHOLOGY OF IRREGULARITIES

The study of irregularities by means of satellite radio signals has been carried out for about one-half of the present sunspot cycle and it is now possible to summarize the results. Related studies have also been carried out by many investigators (Kent, 1959; Liszka, 1963a and b; Munro, 1963; Rawer, 1962; Singleton and Lynch, 1962; Yeh and Swenson, 1959).

IV-1. Diurnal Variation

Scintillation is predominately a nighttime phenomenon but it is observed occasionally in the daytime as well. For comparison purposes, the diurnal behavior of scintillation on 20 mc/s for four seasons near the sunspot maximum (Satellites 1959 Delta 2 and 1959 Iota 1) and on 54 mc/s for similar periods near the sunspot minimum (1961 Omicron 1) are shown in Figs. 9 and 10 respectively. One interesting observation is that the diurnal variation seems weakest in the winter near sunspot minimum.

IV-2. Latitude Dependence of Nighttime Scintillation

The early observations of satellite scintillations at night indicated strong dependence on the geomagnetic latitude. Nearly always, a satellite coming from the north displayed scintillation until it arrived overhead at Urbana; then as it continued southeastward, the scintillation suddenly disappeared and the signal displayed regular Faraday fading. Northbound passages showed transitions in the opposite sense with the scintillation often continuing to the northern radio horizon. This behavior, observed near the sunspot maximum, occurred during more than 20 per cent of all the recorded passages

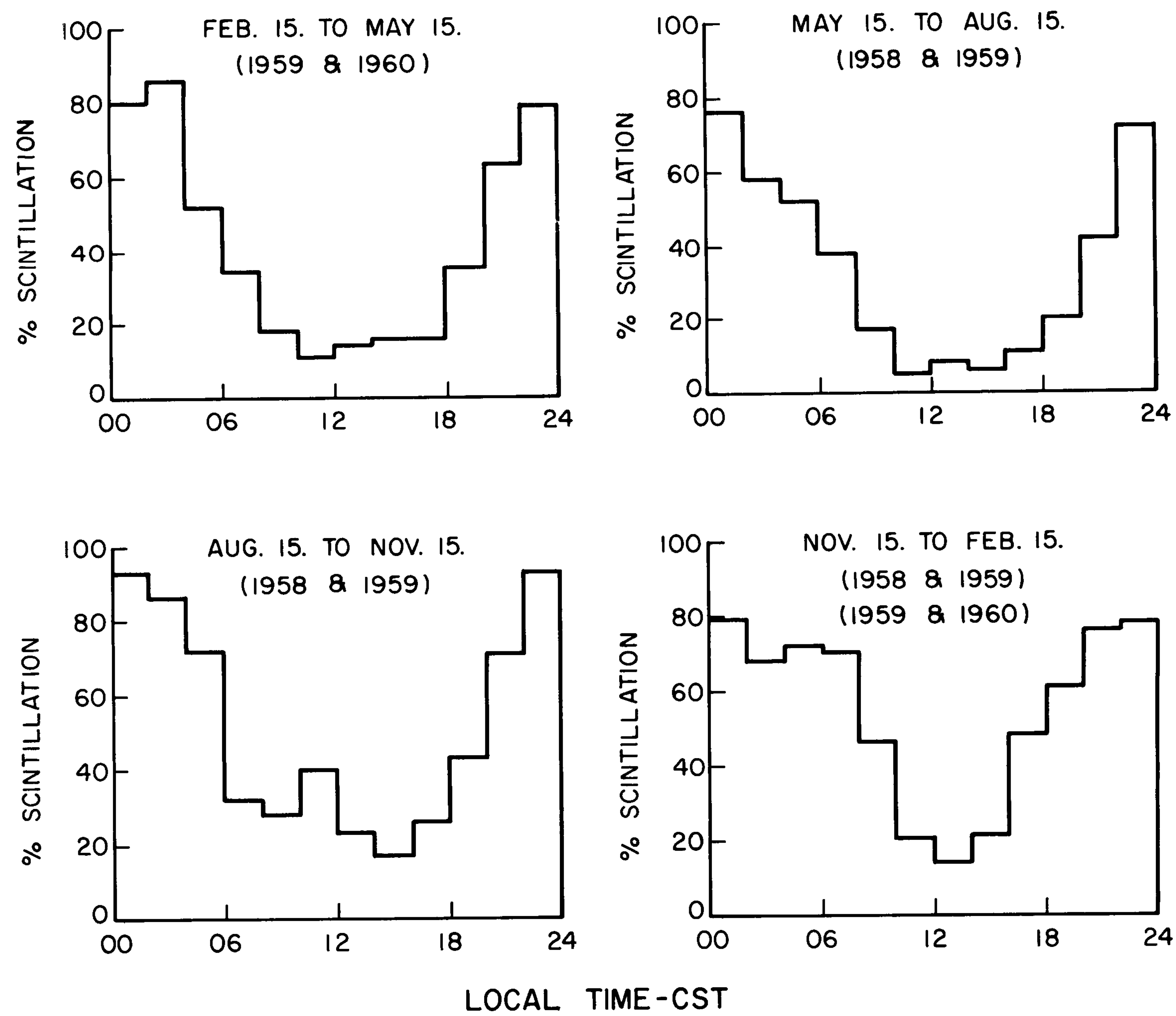

Fig. 9 Diurnal Variation of Scintillation on 20 mc/s Near Sunspot Maximum (1958 Delta 2 and 1959 Iota 1)

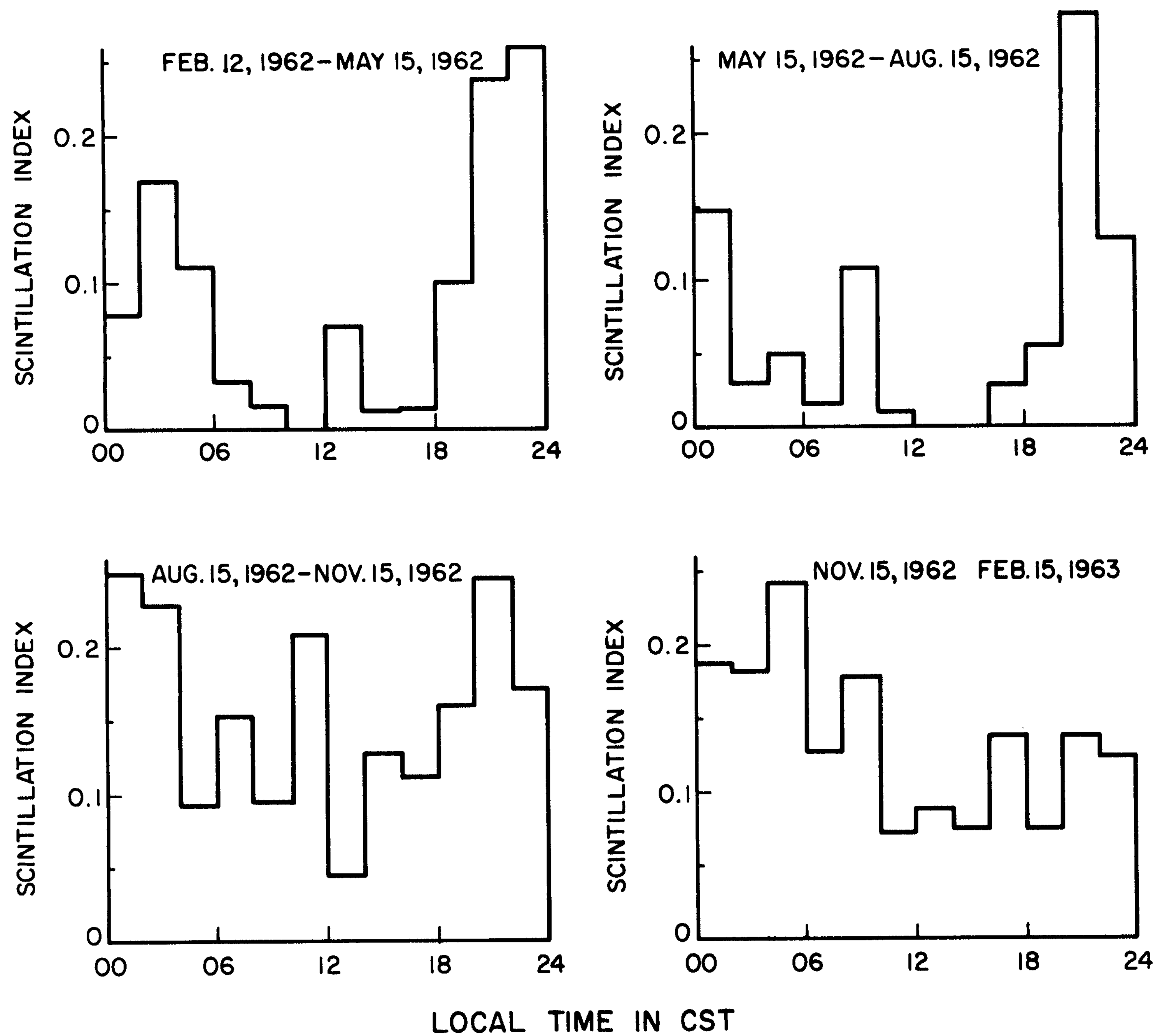

Fig. 10 Diurnal Variation of Scintillation on 54 mc/s **Near** Sunspot Minimum (1961 Omicron)

(See Table 4). Similar transitions have also been reported to occur at Cambridge, England (Kent, 1959); Vancouver, Canada (DeMendonca, 1960); and Boston, Massachusetts (Aarons et al., 1963), which all lie close to the same theoretical auroral isochasm as computed by Vestine and Sibley (1960). A typical group of such transitions is shown in Fig. 11. In computing the location of the transition points it has been assumed that the irregularities occurred at a constant height of 300 km.

Near the end of 1961 a 20 mc/s radio transmitter, Nora-Alice I, was installed on Satellite 1961 $\alpha\ g_1$ (Discoverer 32) and launched into a polar orbit. The satellite remained in orbit for one month. During this period data were obtained at five of the stations listed in Table 1: Aberystwyth, Blaxland, Lower Hutt, Stanford, and Urbana. All of these stations observed transitions at night, as shown in Fig. 12. All lie close to the auroral isochasms "5" (Vestine and Sibley, 1960) in the Northern and Southern Hemispheres, respectively. As the satellite height varied from 220 to 400 km, little error in the geographic position of the transition point is introduced by the assumption that the irregularities are at the same height as the satellite.

Figure 13 shows one example of the statistical behavior of nighttime scintillations as a function of latitude. In this figure no attempt has been made to remove the geometric dependence discussed in III. The variation of scintillation index is interpreted as predominately latitude-dependent for the following reasons: (1) As mentioned earlier, because of the anisotropy in the irregularities, the zenith-angle dependence should be relatively weak, at least in the range considered, (2) The type of records with transitions present indicate strong latitude dependence, and (3) According to the theory (Briggs

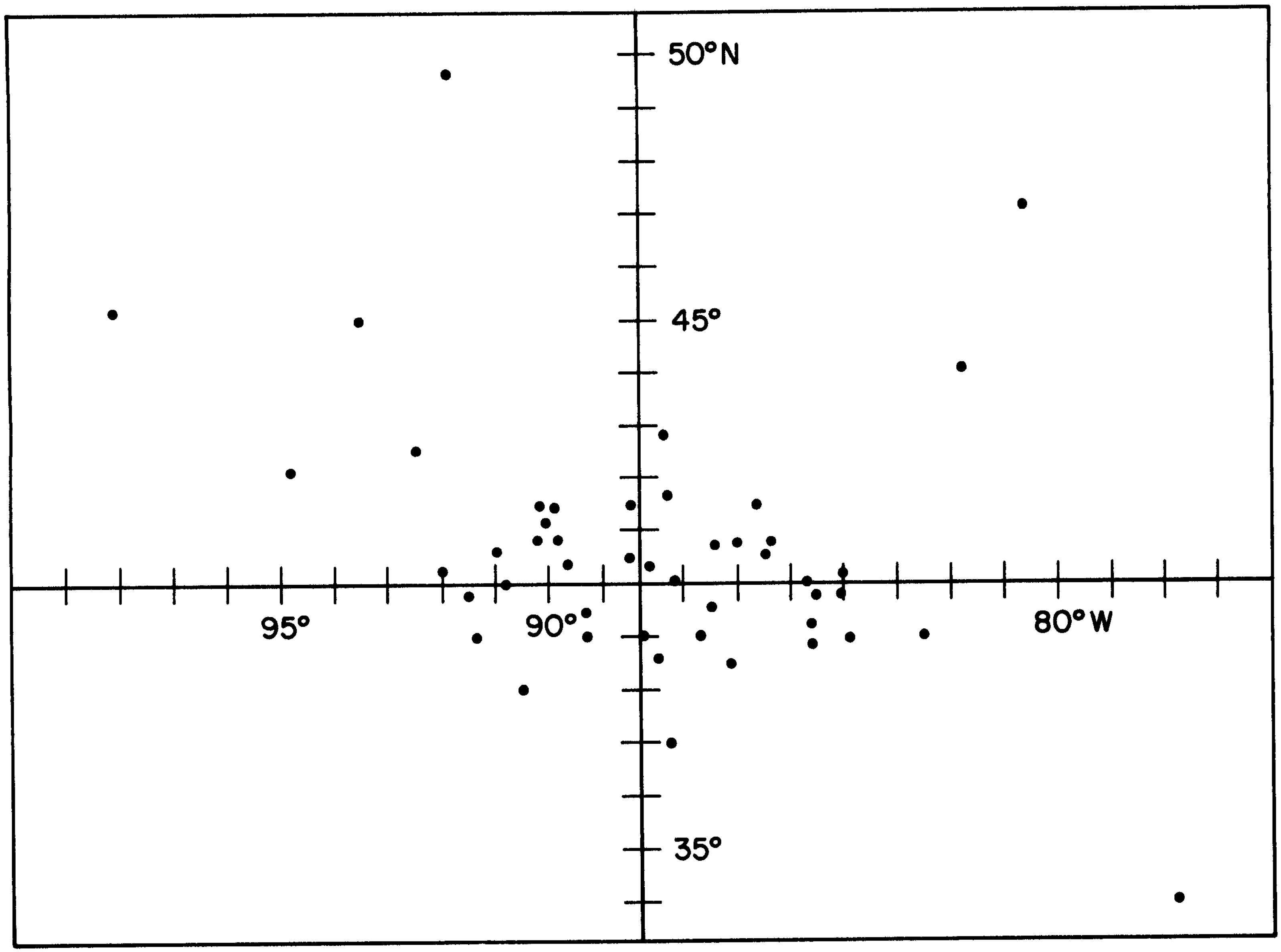

Fig. 11 A Typical Group of Scintillation Transitions Observed at Univ. of Illinois on 20 mc Satellites at Night

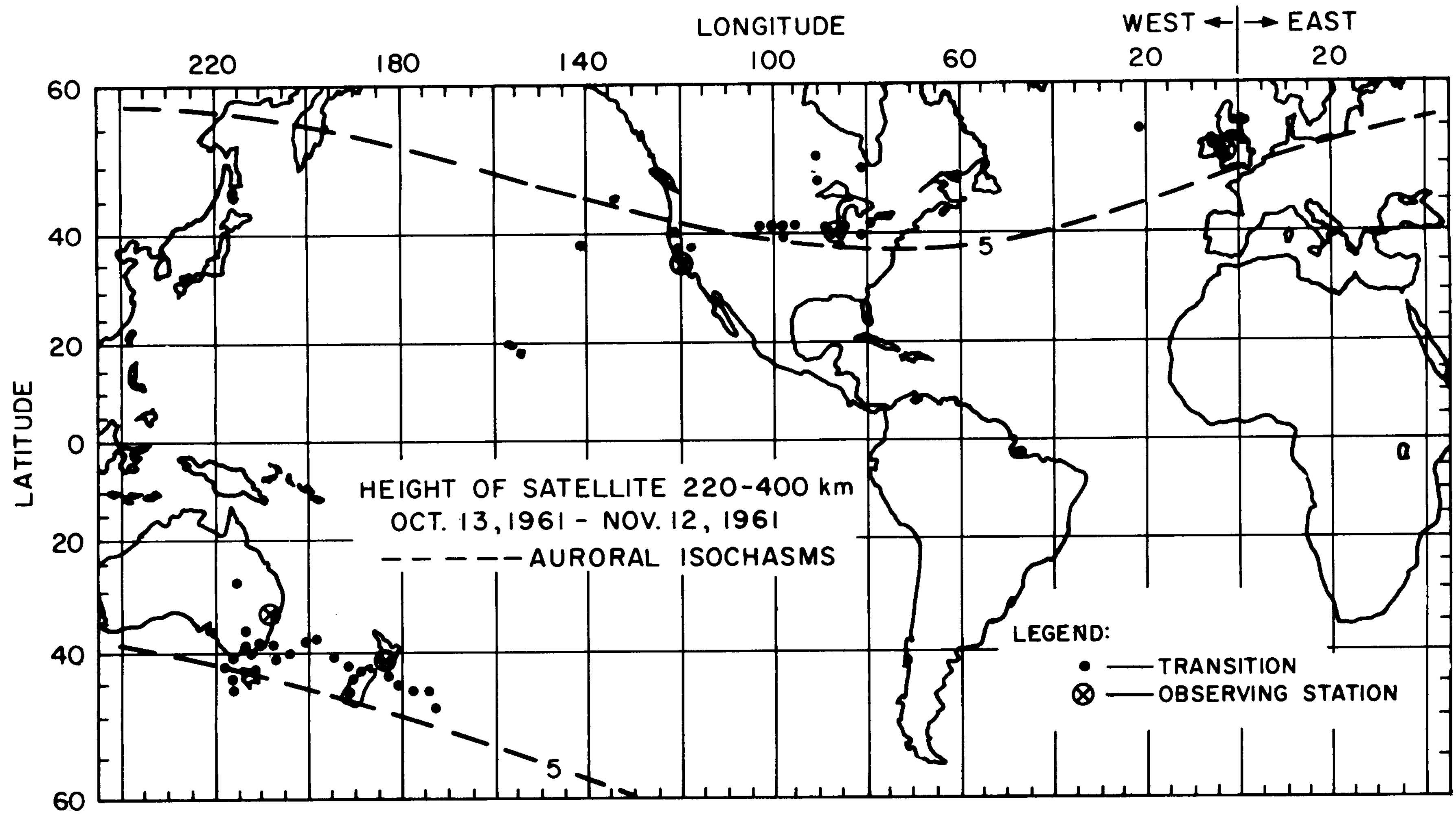

Fig. 12 Transitions of 20 mc/s Signals from Satellite Nora-Alice I (1961 $\alpha\gamma$) Observed Near Local Midnight

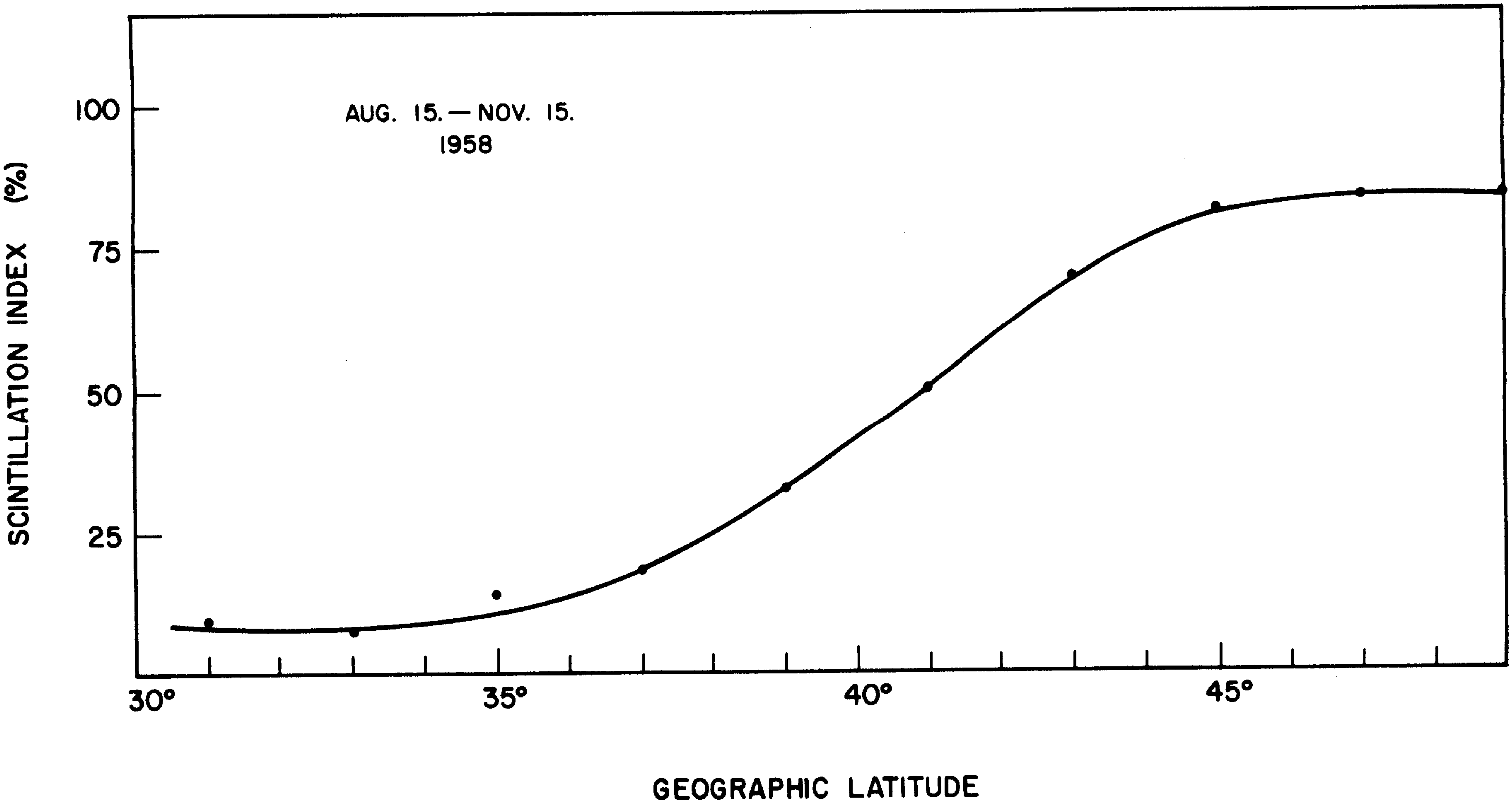

Fig. 13 Latitude Dependence of Nighttime Scintillations on 20 mc/s

and Parkin, 1963; Yeh, 1962) and observational evidence (Singleton and Lynch, 1962) scintillations should be more pronounced when propagation is parallel with the Earth's magnetic field lines than when it is perpendicular to the field lines. (The opposite suggestion of Mawdsley, 1960, has been criticized by Frihagen and Trøim, 1961; Briggs and Parkin, 1963; and Singleton and Lynch, 1962). For an observer in the northern hemisphere this means that the scintillation dependence due to zenith angle alone should be more pronounced when the satellite is to the south (lower latitude) than when it is to the north (higher latitude). Such an effect does not show up in Fig. 13. The conclusion is that near sunspot maximum the latitude dependence is so strong that it overshadows other minor effects.

An example of scintillation dependence on latitude during sunspot minimum is shown in Fig. 14. Here the behavior is distinctly different; i.e., the maximum scintillation does not occur at high latitude, but rather slightly to the south of the observer (40°N). To investigate whether or not Fig. 14 is contaminated by the aspect-of-propagation effect discussed above and in section III it is necessary to examine the azimuth angle dependence. The result is shown in Fig. 15, in which are plotted those portions of nighttime passages having a zenith angle 40°-50°. From the magnetic aspect argument the scintillation is expected to be maximum in the magnetic south direction, corresponding to an azimuth of 186°. In Fig. 15 the two maxima appear only slightly to the south of the observer's latitude in agreement with Fig. 14 and no maximum appears to the magnetic south. Certainly Fig. 13 and Fig. 14 are contaminated by factors other than the latitude effect, but such contamination must be small, especially during sunspot maximum.

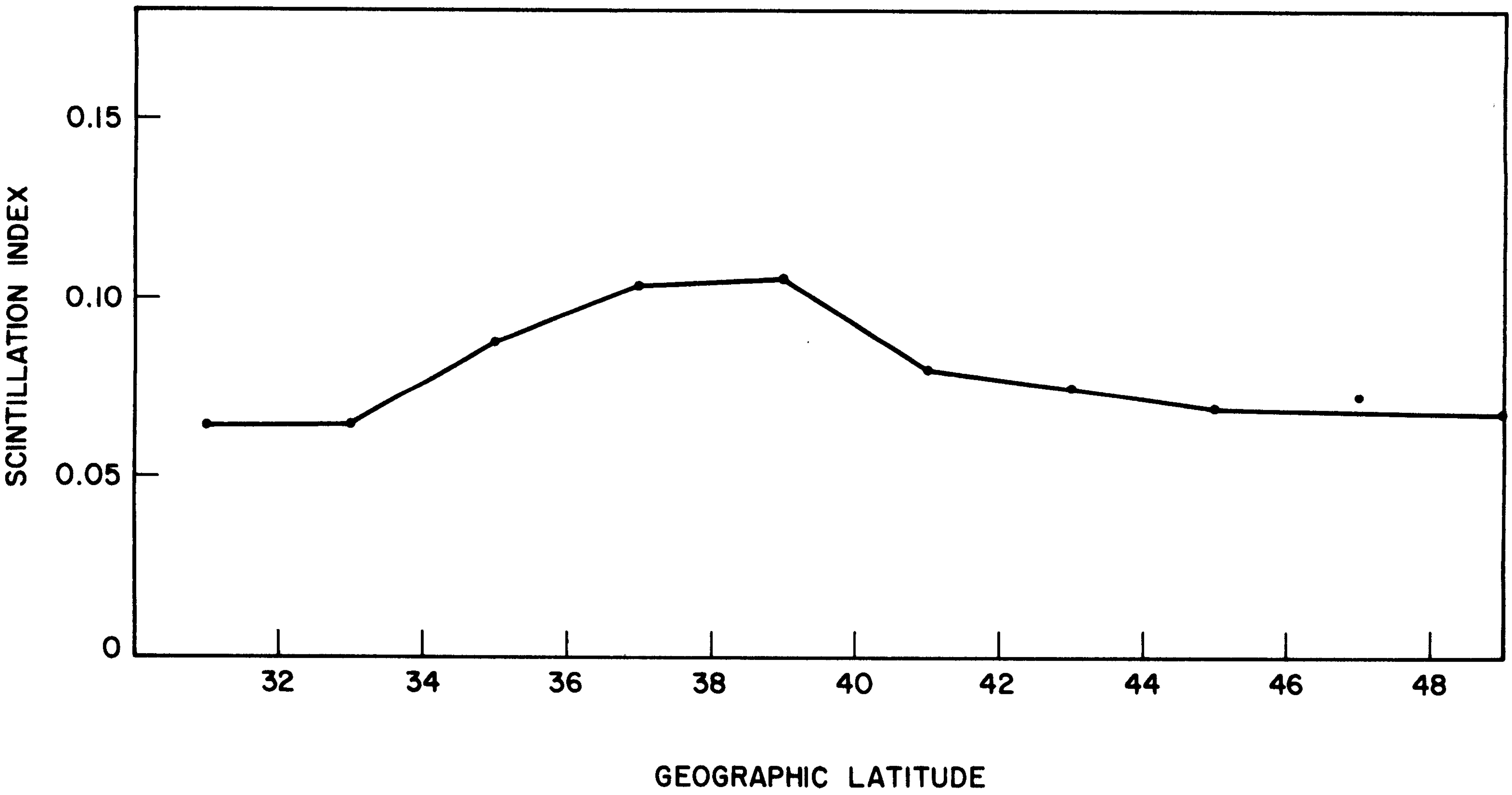

Fig. 14 Latitude Dependence of Nighttime Scintillation on 54 mc/s (1962 Winter)

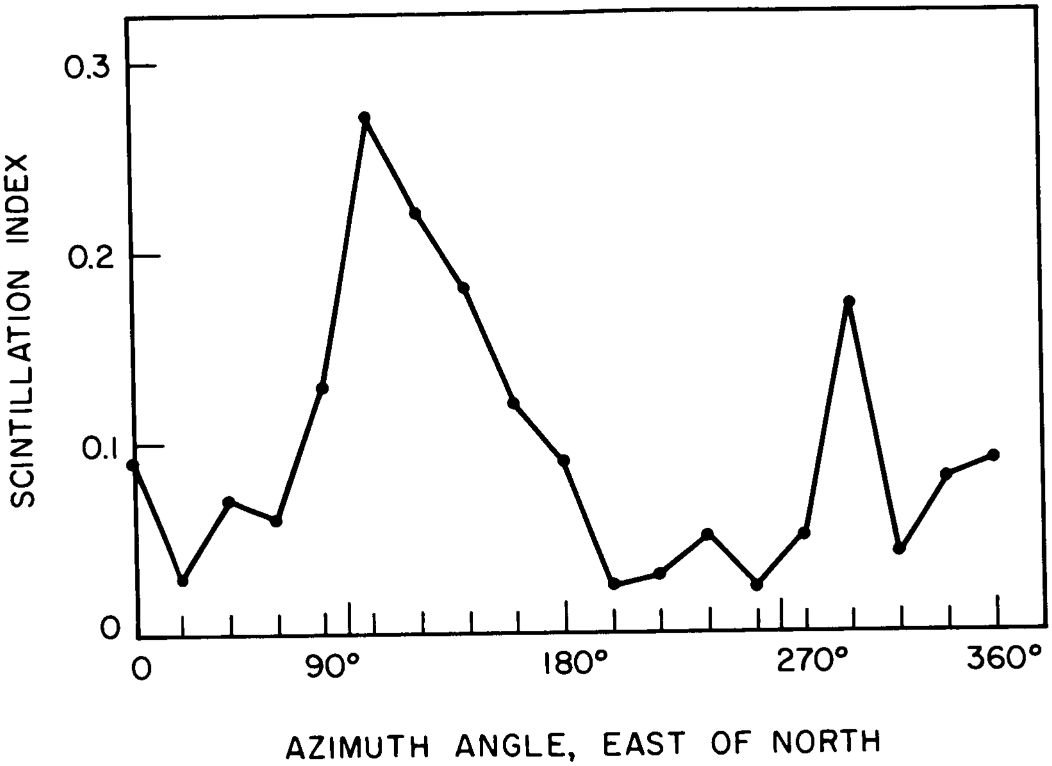

Fig. 15 Azimuth Dependence of Scintillation on 54 mc/s (1962 Winter, Nighttime Passages with Zenith Angle 40°-50°)

IV-3. Seasonal and Sunspot Dependence of Nighttime Scintillation

Studies such as that carried out in IV-2, for a total of thirteen seasons, are combined into a contour plot in Fig. 16. Also shown in the figure is the smoothed sunspot number. The following observations can be made:

1) During the sunspot maximum the average scintillation index increases sharply at about 40^{o} geographic latitude for all seasons.
2) At high latitudes and during sunspot maximum the average scintillation index is maximum in the fall season and minimum in the summer season, while such seasonal dependence is not apparent at a latitude below 40^{o} N or during sunspot minimum.
3) From 1958 to 1960 as the sunspot number decreases there is a general decrease of scintillation superposed on the seasonal dependence. This is especially clear if one compares the maximum scintillation from year to year.

It should be emphasized that the contour plots in Fig. 16 represent only the average behavior. Actually the scintillation is quite variable from day to day, especially during sunspot maximum. For this reason the average scintillation index and the unbiased estimate of the variance are shown in Table 6.

IV-4. The Daytime Scintillation

The scintillation in the daytime does not show a systematic latitude dependence as does the nighttime scintillation. However, both seasonal and sunspot dependences are quite pronounced as shown in Fig. 17. From this figure the winter maximum and the summer minimum can be determined, as well as the trend through the years of declining sunspot number. The behavior in 1962 is

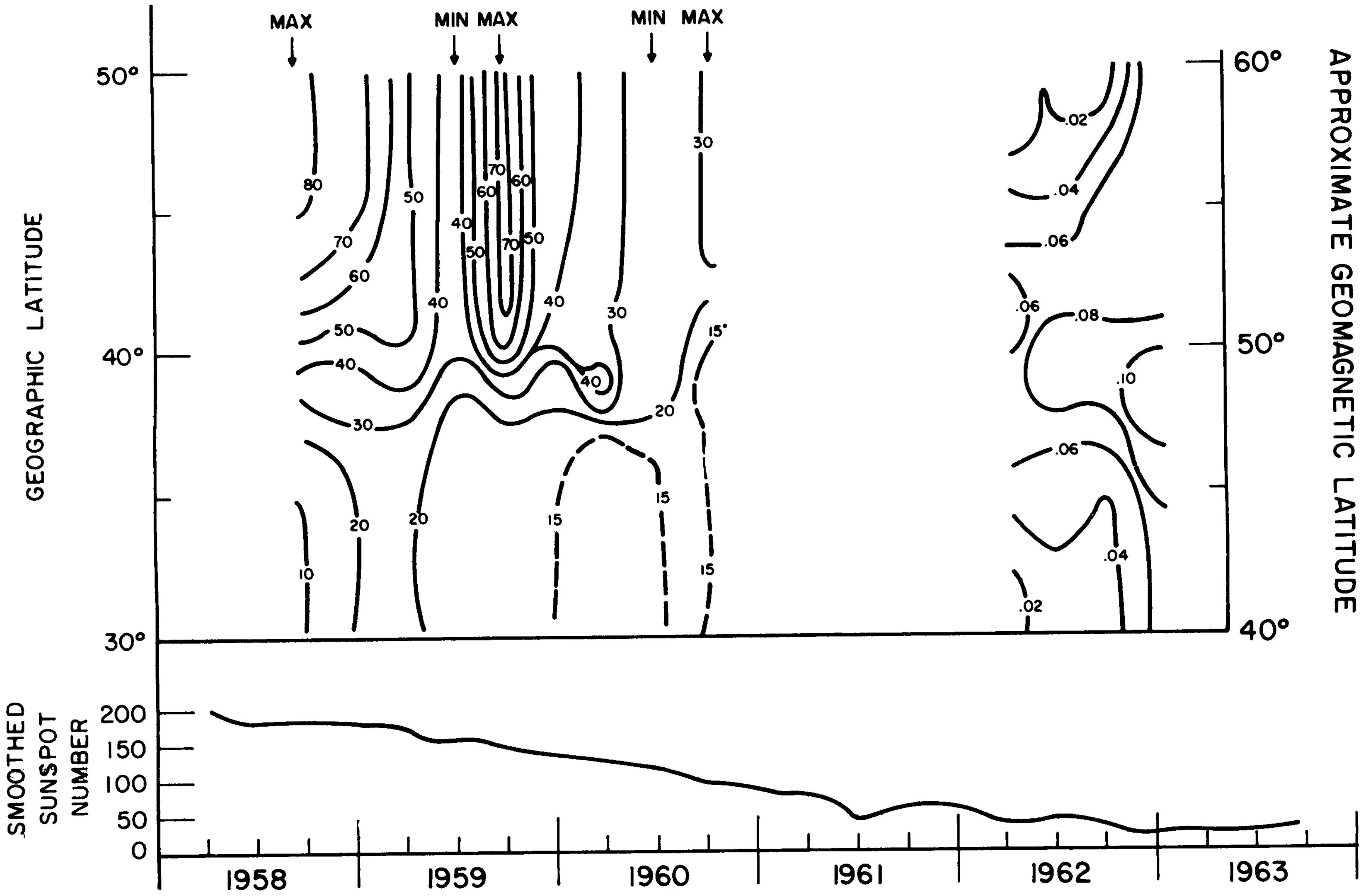

Fig. 16 Contours of Equal Average Scintillation on 20 mc/s (Percent) and on 54 mc/s (Scintillation Index) Near 88° W

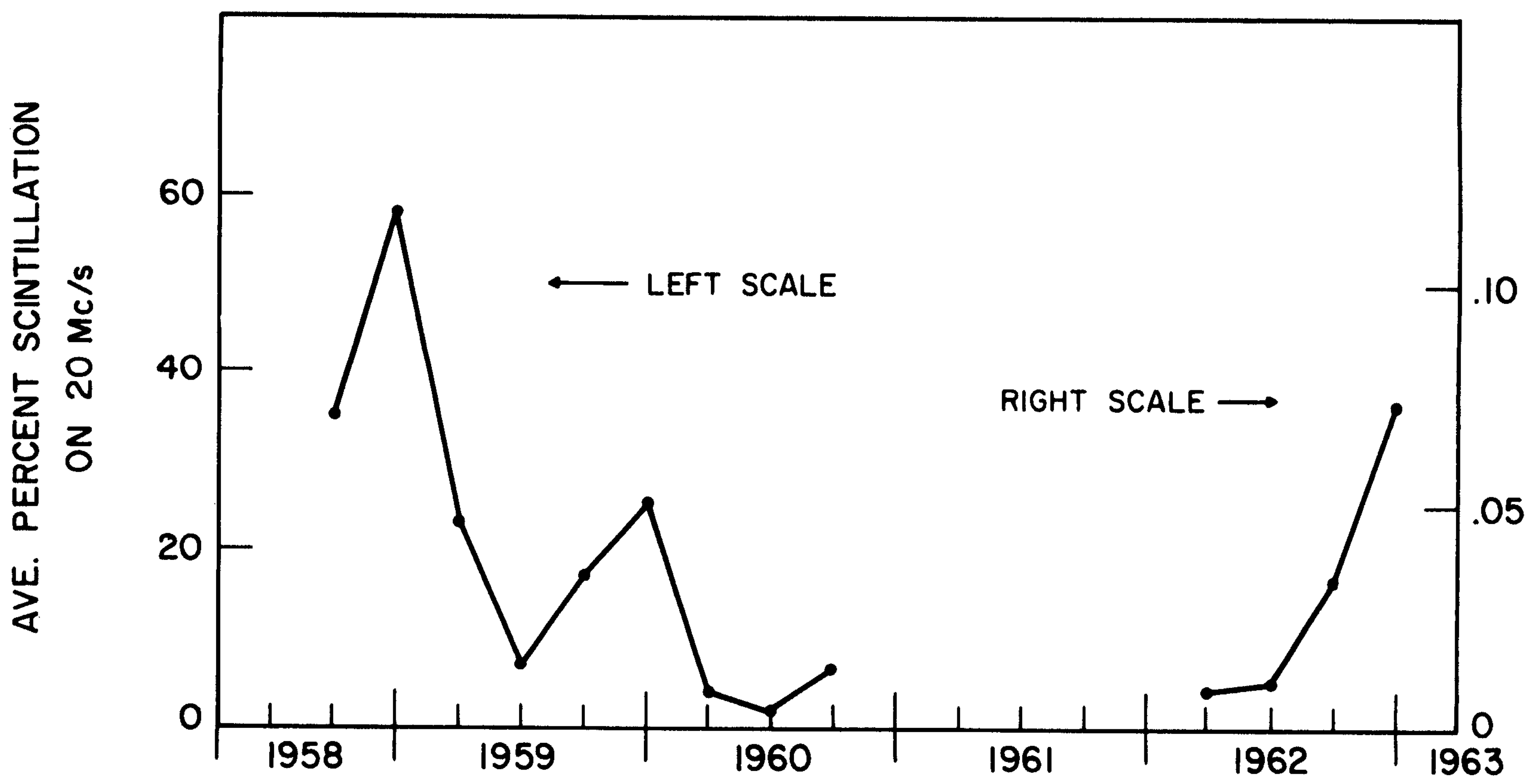

Fig. 17 Seasonal and Yearly Dependence of Daytime Scintillation

not yet clear, even though it is not inconsistent with the behavior during sunspot maximum, additional data reduction is necessary to clear up this point.

IV-5. Magnetic Activity Dependence

The maximum scintillation index observed during each nighttime satellite passage has been correlated with the planetary magnetic index, K_p. The correlation coefficient is 0.15 for the period September, 1958 to October, 1960 on 20 mc/s signals and 0.13 for the period February, 1962 to February, 1963 on 54 mc/s signals. Therefore, the correlation of the scintillation index with the planetary magnetic index is small and positive.

When transition latitude is correlated with K_p, the resulting coefficient is -0.15. This indicates the tendency of these transitions to move to a lower latitude when magnetic activity increases. Such an effect has also been noted by Aarons et al., (1963).

Table 6. Average and Variance of Scintillation Index on 54 mc/s in 1962

(Nighttime Passages Only)

Period	Latitude										Number of Records
	30^{o}-32^{o}	32^{o}-34^{o}	34^{o}-36^{o}	36^{o}-38^{o}	38^{o}-40^{o}	40^{o}-42^{o}	42^{o}-44^{o}	44^{o}-46^{o}	46^{o}-48^{o}	48^{o}-50^{o}	
Spring	.007±.001	.024±.007	.054±.020	.071±.025	.067±.020	.045±.008	.067±.020	.045±.001	.015±.003	.004±.001	82
Summer	.035±.014	.041±.014	.041±.013	.071±.017	.088±.024	.082±.026	.061±.018	.041±.009	.033±.009	.024±.008	66
Fall	.025±.006	.015±.003	.046±.011	.065±.021	.085±.024	.080±.019	.063±.027	.069±.018	.042±.013	.012±.003	81
Winter	.064±.005	.064±.007	.087±.016	.103±.025	.105±.025	.080±.019	.075±,014	.069±.005	.072±.045	.067±.004	76

V. RELATION TO OTHER OBSERVATIONS

V-1. Relation to Irregularities Observed by Other Radio Techniques

The correlation of the occurrence of irregularities observed by various techniques has been a subject of study by many authors (Briggs, 1958a and b; Calvert, et al., 1962; Carpenter and Colin, 1963; Chivers, 1960b; Lawrence, et al., 1961; Peterson, et al., 1955; Singleton and Lynch, 1962). An extensive study of the morphology of ionospheric irregularities has been carried out by the study of spread-F (Shimazaki, 1959; Singleton, 1960 and 1962) and by the study of radio star scintillation (Booker, 1958).

The diurnal variations given by Figs. 9 and 10 generally agree with other observations, especially with regard to the maximum at night. The present result indicates there is some daytime activity which was not observed at Cambridge and which was observed in Australia with a daytime peak almost as large as the nighttime peak. The discrepancy in daytime behavior is often blamed on sporadic-E. No sporadic-E statistics are available for comparison with the scintillation data presented herein. However, the present data do suggest that, on the average, the daytime scintillation and the nighttime scintillation behave differently in their latitude and seasonal variations.

The experimental observations of radio star scintillation have not been in agreement with respect to seasonal variation. For example, in Australia (Bolton et al., 1953) winter and summer maxima and spring and fall minima were observed, while in Canada (Hartz, 1955) no apparent seasonal dependence was reported. It is not known whether such observational discrepancies can be reconciled by taking sporadic-E, aurora, low angle of observation, latitude effect, variation of f_oF2, sunspot cycle and errors in sampling into account.

Lawrence, et al. (1960), utilizing the cosmic radio source Cygnus A, observed minimum scintillation activity in the fall and maximum in the spring. This is inconsistent with the present data, and is probably due to the fact that Cygnus A is seen during hours of darkness at their location (Boulder, Colorado) only from March through June. As the satellite data clearly shows, F-region scintillation occurs almost exclusively at night. The seasonal dependence of spread-F, as studied by Shimazaki (1959), is such that the probability of occurrence, at latitudes higher than 30° geomagnetic, is higher in winter than in summer at sunspot maximum. The probability in the fall may at some stations be comparable to that in winter. Thus, the present observations are in general agreement with the spread-F study, especially if allowances are made for differences in observing techniques.

The dependence on latitude given by Figs. 13 and 16 is in good agreement with spread-F observations (Shimazaki, 1959) in its behavior both in the sunspot maximum and in the sunspot minimum. During sunspot maximum years the scintillation index as well as the probability of occurrence of spread-F increases rapidly as geomagnetic latitude increases from 40°N to 60°N. Due to averaging of data such an increase appears to take place over roughly 5° in latitude. Satellite observations indicate that in many instances such transitions may be very abrupt, say 10 km or less. These transition boundaries exist both in the northern and southern hemispheres and at approximately the same auroral isochasms, as indicated by the Nora-Alice experiment. Study of radio star scintillation also indicates a closer connection between the scintillation occurring at higher latitudes in the two hemispheres than between that at high latitudes and at the equator (Brenan, 1960). In view of this sharp edge effect the correlation between spread-F at two vertical sounders separated by several hundred kilometers would not be expected to be perfect.

The relationship between magnetic activity and irregularities has been studied by a number of authors. Its correlation with spread-F in geomagnetic latitudes 30^{o}-60^{o} is in the neighborhood of +0.2 to +0.3 (Shimazaki, 1959). Peterson, et al., (1955) observed negligible correlation between magnetic activity and backscatter from field-aligned irregularities. The present investigation yields a correlation of +0.13 to 0.15 (See IV-5). Thus, the correlation of magnetic activity with irregularities is not as striking as with auroral activities, but it is positive.

V-2 Relation to Subvisual Red Auroral Arc, Precipitation of Energetic Electrons and the Radiation Belts

The occurrence of monochromatic (6300 Å) subvisual auroral arcs in mid-latitudes was discovered by Barbier (1958). Since then extensive observations have been carried out in both southern (Duncan, 1959) and northern hemispheres. These arcs occur at times when there is general auroral activity to the north. But there are differences between these two phenomena especially in their geographic positions and their time variations. The heights of maximum luminosity are around 400 km (Roach et al., 1960; Moore and Odencrantz, 1961). During a severe geomagnetic storm on November 28, 1959 two Geiger tubes on satellite 1959 Iota (Explorer 7) detected anomalies in the outer radiation zone at a height of about 1000 km. These anomalies appeared to correlate in space and time on a number of satellite passes with the observation of subvisual 6300 Å arcs in the F region. The brightness of these arcs diminished as the radiation zones became less intense (O'Brien et al., 1960). Based on the observation of an arc on the night of November 27, 1959, King and Roach (1961) explained the emission in terms of an enhancement by three orders of magnitude of the ionospheric recombination coefficient. More recently Roach (1963) found scintillation on the very high frequency radio signals propagated from a polar orbiting satellite through 6300 Å red arcs and determined that the scintillation "noise power" (See II-1) correlates logarithmically with the photon flux determined from the photometric measurements.

In view of the suggested connection between subvisual 6300 Å arcs and scintillation phenomenon Table 7 has been prepared to show the satellite radio scintillation observations on nights when red arcs were seen and published in the literature. This table shows that during the appearance of red arcs scintillation was simultaneously observed. Subsequent daytime observations indicated little scintillation if any.

Table 7. Transition Latitudes of Satellite Scintillation Observed at Times of Appearance of Red Arcs (6300 Å)

Date	CST	Transition Latitudes	Remarks	Literary Reference
Oct. 22, 1958	2059	41.9°N	sharp transition	Roach & Marovich, 1960
Nov. 27, 1959	1250	—	no scintillation	
Nov. 27, 1959	1955	41.7°N	transition (30 sec.)	Roach et al., 1960
Nov. 28, 1959	0115	—	strong scintillation throughout the passage	O'Brien et al., 1960
April 2, 1960	0023	—	strong scintillation throughout the passage	Moore and Odencrantz, 1960
April 2, 1960	0551	—	scintillation throughout the passage	
April 2, 1960	0928	—	only one small patch of scintillation	
Oct. 1, 1961	0052	37.9°	fairly sharp transition	Tohmatsee & Roach, 1962

In the following a more detailed discussion of each of these events is given.

A) October 22, 1959 Event: Auroral activities observed to the north. At 2100 CST the boundary of the 6300 A arc was at about 53°N geomagnetic and the scintillation boundary was found to be at about 52°N geomagnetic (or 42°N geographic). Since the determination of the boundary requires the assumption of height in both observations such correspondence is considered to be good.

B) November 27-28, 1959 Event: Sudden commencement at 1750 CST November 27. Auroras observed. Close correlation of the aurora and the red arc with the outer radiation belt (O'Brien et al., 1960). The 1955 CST pass had a transition roughly at 42°N and the 0115 CST pass had scintillation throughout the passage. The first photometric observation was made at 2222 CST when the arc was moving steadily south. At 0115 CST, the band of the red arc appeared within the dip angle range 66°-72° while the radiation counting rate had a maximum near this range and decreased but was still appreciable to the north of the band and decreased to a negligibly small amount to the south of the band. The height of the red arc was found to be at 400 km by triangulation (Roach et al., 1960). These observations are quite compatible with the scintillation results.

C) April 1-2, 1960 Event: Magnetic storm occurred. During the period 0015 to 0515 CST the height of the red arc was determined to be slightly above 400 km and its geographic position was fairly constant in the dip angle range 65°-67°. Very strong scintillation was observed at 0023 CST almost throughout the passage except to the far south where the scintillation was slightly weaker. The scintillation at 0551 CST was weaker than at 0023 CST and the scintillation was very weak south of 35.9°N. Again, the scintillation observation suggests its correlation with the red arc. The observation next day at 0928 CST indicated only one small patch of irregularities.

D) September 30-October 1, 1961 Event: Red arcs observed (Tohmatsu and Roach, 1962) at Fritz Peak (39.9°N, 105.5°W, 49° geomagnetic). At 2130 the arc extended 20° south to 40° north in zenith angle and at 2144 it extended 5° south to 45° north in zenith angle at Fritz Peak. The scintillation observation one and one-half hours later indicated the southern boundary at 38°N or 48° geomagnetic which compares favorably with the red arc observation.

The observation of these four events, the agreement in heights of red arcs and the irregularities and also the work of Roach (1963) suggest strongly that when the ionosphere is perturbed sufficiently during the presence of red arcs the radio signals passing through it will scintillate. However, the converse is not necessarily true since red arcs are fairly rare while scintillation is quite common, and red arcs are correlated with magnetic activity while the scintillation has very weak correlation with magnetic activity. It seems plausible, therefore, that the ionosphere is constantly perturbed by some agency so that scintillation is a common phenomenon at night, especially near sunspot maximum, and if such perturbation is intense enough it may also excite red arcs.

The study of the trapped radiation from the satellite Explorer VI first showed the existence of the bifurcation of the outer belt (Fan et al., 1960). Stolov (1962) postulated that the E_2 belt might be responsible for the red arc phenomena and the E_3 for the aurora. Additional observations showed that the radiation is strongly varying and may at times have double or multiple peaks (Van Allen, 1961). Positions of the maximum intensity of the outer zone plotted by Lin and Van Allen (Van Allen, 1961) agree with the latitude dependence of the scintillation if we postulate that the leakage of the energetic particles near the horn of the outer zone, just above the bottom of exosphere, is responsible for the occurrence of irregularities. Such a postulate has been made previously (Peterson, et al., 1955; Shimazaki, 1959; and many others). O'Brien and Laughlin (1963) suggest that the dumped electrons may not be sufficiently energetic to excite the 6300 Å line of the red arc.

VI. A POSSIBLE CAUSE OF IRREGULARITIES

Theories of the production of irregularities have been proposed by many authors and most of them encounter some difficulties. These have been reviewed by Dagg, (1957) and Singleton, (1962). More recently Farley (1963) and Buneman (1963) proposed that the strong horizontal currents in the equator and the auroral zone may excite two-stream instabilities and create density fluctuations in the E region. Further computations using actual geomagnetic observations support these proposals (Maeda, et al., 1963). Experimental data of Bowles, et al., (1963) have identified these irregularities as acoustic plasma waves and hence also support the theory. However, the theory as originally presented had difficulty in explaining irregularities in the F region observed in the temperate latitudes because of the lack of strong horizontal currents.

According to Fig. 6 most irregularities occur at about 350 km height. The normal atmospheric processes that take place are the ambipolar diffusion and the attachment-like process. These processes are quite complicated since the ionosphere is a non-homogeneous plasma (i.e., height dependent). For estimation purposes the situation will be simplified drastically by assuming the medium to be homogeneous with values appropriate to 350 km height. The characteristic time of diffusion is given by the ratio of the square of the scale height of atomic oxygen to the ambipolar diffusion coefficient. Using the number densities computed by Harris and Priester (1962) for the sunspot maximum the characteristic time of diffusion at 350 km is computed to be 2.9 hours at night and 8.0 hours near noon. The characteristic time of "attachment" is given by the inverse of the product of the rate of the dissociative recombination and the density of molecular oxygen (or molecular nitrogen). Using the rates obtained by Nisbet and Quinn (1963) the "attachment" time at 350 km is found to be 4.1 hours at night and 1.5 hours near noon. Hence any other process that may be important in the ionosphere must be able to compete with the diffusion and "attachment" and have a time constant not more than a few hours.

The Injun I and Explorer 12 satellites measured the flux of electrons in the outer radiation belt with energies 40 kev or greater, dumped in temperate latitudes, to be of the order 10^3 to 10^4 particles/cm^2-sec-sr, (O'Brien and Laughlin, 1963). This corresponds to a number density of 5×10^{-7} to 5×10^{-6} electrons/cm^3 or to an angular plasma frequency of 4×10^{-2} to 1.3×10^{-1} rad/sec, extremely small compared with the ambient ionospheric plasma frequency of about 3×10^7 rad/sec. Since the dumped electrons are drifting along the magnetic field, two-stream instability is possible. However the instability is important only if the growth can compete with diffusion and "attachment". The linearized theory of two stream instability has been studied by a number of authors. Using the beam equations and assuming positive charges to form a neutralizing background one obtains the dispersion relation (Stix, 1962)*

$$1 = \frac{\omega_p^2}{\omega^2} + \frac{\omega_{pd}^2}{(\omega - kV)^2} \tag{1}$$

where ω_p is the ionospheric plasma frequency, ω_{pd} the plasma frequency of the drifting electrons dumped from the radiation belt, V the drifting velocity, k the wave number in the direction of V (a real number), and ω the angular frequency which may be complex. The dispersion relation is a quartic equation in ω and has four roots. Since $\omega_p \gg \omega_{pd}$, two of the four roots occur at

*It should be remarked that the interparticle distance of the dumped electrons is larger than the Debye length in the ionosphere, the fluid model adopted here may have a questionable validity.

approximately $\pm\,\omega_p$ which correspond to the usual plasma oscillation modes and are of no interest here since growing modes are needed. Also because $\omega_p \gg \omega_{pd}$, the two remaining roots occur when ω is very near kV. Making these approximations one finds that growth is possible if

$$\omega_p > kV \tag{2}$$

This condition is easily satisfied since $\omega_p = 3 \times 10^7$ rad/sec, $kV = 8 \times 10^4$/sec (corresponding with irregularities of approximately 5 km). The two remaining modes are given by (assuming $\omega_p \gg kV$)

$$\omega = kV \pm i\,\frac{kV\,\omega_{pd}}{\omega_p} \tag{3}$$

The imaginary part of ω indicates instability. The growth time of the instability is given by

$$\tau = \frac{\omega_p}{kV\,\omega_{pd}} \tag{4}$$

Using the experimentally observed data of O'Brien and Laughlin (1963) one obtains $\tau = 0.9 - 3$ hours. Therefore, the experimentally observed data on dumping indicate that plasma oscillations of wavelength approximately 5 km can be excited, whose growth time can compete with diffusion and "attachment" near the sunspot maximum.

The preliminary satellite data of O'Brien and Laughlin (1963) showed dumping from L = 2 to 14.8. The precipitation showed extremely complex structure during each satellite pass. This suggests that dumping is by no means unifrom. On the average, significant dumping seems to commence at $L = 2.42$ which corresponds to roughly $40^{O}N$ at Urbana. The flux of dumped electrons decreases to the south and increases to the north of this L shell. Both the location and the latitude dependence indicate good agreement between the dumping and the latitude dependence of scintillation. The comparison of diurnal behavior of scintillation and precipitation is not possible because of lack of information on the latter. The seasonal and sunspot dependences may be caused by either or both of the following possibilities: (1) The dumping may have seasonal and sunspot dependences and (2) The atmosphere has a seasonal and sunspot dependence . While (1) is not yet clear, there is ample experimental evidence to support (2). Since there is not yet good agreement on scintillation seasonal dependence no further comment will be made. As far as the sunspot dependence is concerned it is observed that the upper atmosphere density decreases in the declining sunspot years. Since the diffusion time is proportional to temperature squared and the number density of atomic oxygen (ignoring the small temperature dependence of mobility) and the temperature and the atomic oxygen density decrease markedly toward the sunspot minimum, the diffusion at 350 km may become so fast that the growth time cannot compete with it. If the theoretically predicted number density (Harris and Priester, 1962) is used, the computed diffusion time is 0.05 hour at sunspot minimum. The number 0.05 hour probably is too small to be realistic; at least it indicates that during sunspot minimum only in regions in which the dumping is sufficiently intense in both energy and density (See Eq. 4) can the growth be sufficiently rapid to compete with diffusion. This again is in agreement with the latitude dependence of scintillation during sunspot minimum. Since the electron flux dumped is small its associated current is small and hence the occurrence of irregularities should not be highly correlated with magnetic activity. Note that the diffusion time is proportional to the density of atomic oxygen while the "attachment" time is inversely proportional to the density of molecular oxygen. Hence the growth is less favored for a height much above the F2 peak where diffusion is very fast, or for a height much below the F2 peak where recombination is very fast. This explains the concentration of irregularities near the F2 peak, as shown in Fig. 6.

An elementary theory has been proposed here for the production of F region irregularities in temperate latitudes. A more refined theory will also involve the effects of gradients of the various ionospheric quantities. Apparently the theory has difficulty in explaining the measured 1 km scale of irregularities in the direction perpendicular to the magnetic field. It is not known whether or not the scale size across the field is related to the dumping mechanism since the ion gyroradius has about the same order of magnitude. Of course, there are other types of irregularities observed in the ionosphere, such as equatorial F-region irregularities, which may require entirely different mechanisms to explain their existence.

If the above proposed mechanism for the production of temperate latitude irregularities in the F region is reasonable and is proved to be correct by more experimental data, it suggests a new method of studying precipitation of electrons from the radiation belts.

VII. ACKNOWLEDGEMENT

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